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Application of Beidou Navigation Signal Enhancement Technology in Agricultural Machinery Operation Under a Complex Farmland Environment

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Abstract

Navigational systems with high accuracy capabilities are essential modern tools for sophisticated agricultural operations, particularly when used in challenging environments. For fully automated agrarian vehicles, the BeiDou Navigation Satellite System, when combined with RTK and inertial navigation systems, provides high accuracy at a reasonable cost. This paper focuses on enhancing the BeiDou System for better navigation accuracy under farmland complexities like signal blockage, multipath interference, and rough terrain. A low-cost RTK-BDS/INS navigation system, which employs Kalman filtering and multipath reduction techniques, was built. Testing in various areas, including open fields, densely vegetated regions, and those with obstructed signals, demonstrated that the system achieved position accuracy better than 3 cm in open areas and better than 10 cm in more obstructed environments. The system was validated for accuracy, resilience, and real-time performance and was found to have improved flexibility, speed, and efficiency in operation. In addition, precision agriculture through IoT and 5G sensors enabled advanced autonomous controls for tasks such as precision seeding, fertilization, and path following. This approach facilitates further development in machine automation for sustainable agriculture, advancing precision and conventional farming systems through data integration.

Keywords:

Beidou navigation satellite system (BDS), precision agriculture, RTK-BDS/INS integration, autonomous agricultural machinery, signal enhancement, complex farmland.

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Introduction

The emergence of smart farming is enhancing conventional agriculture through automation, precision, and operation based on detailed data analytics. In modern farming, autonomous agricultural vehicles play a pivotal role, especially with the growing need for increased production, efficient resource utilization, and lower cost

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of human labor. In the robotics and remote-controlled farming machinery sector, the automation of unmanned tractors, seeders, and harvesters is being accomplished with the use of real-time satellite-based navigation and geo-positioning systems (Hafezieh, 2024). Compared to other GNSS systems such as GPS and GLONASS, BDS has proven to be more advantageous for agricultural purposes in China and neighboring countries due to its greater coverage over Asia-Pacific and quicker commercialization of regional and global constellations (Li & Gu., 2025; Mousazadeh, 2013; Alshwani & Bilal, 2025).

Problem Statement

The implementation of BDS in multifaceted farmland surroundings, which include steep slopes, dense vegetation, orchards, and infrastructural intrusions, holds critical challenges. The BDS signal suffers from multipath propagation, non-line-of-sight (NLOS) reception, and sporadic signal availability in shadowed zones and the transitional regions between open fields and obstructed plots. These challenges impede the precision and continuity required for seamless, sub-centimeter level accuracy in variable-rate fertilization, automatic tillage, and path-following (Yong et al., 2024). Although standalone BDS and standard RTK-GNSS systems perform reasonably well in open-sky environments, their functionality in intricate agricultural terrains devoid of superordinate algorithms is severely limited (Xia, 2020).

Objective of the Study

This study focuses on developing and assessing a signal enhancement framework for Beidou-based agricultural navigation systems used in precision farming, taking into consideration the harsh conditions of the fields. The primary goal is to achieve real-time kinematic (RTK) accuracy by combining it with inertial navigation systems (INS) and advanced artificial intelligence-based filtering techniques to reduce signal loss, ensuring uninterrupted high-precision navigation during fully automated operations over heterogeneous topographical and geological landscape profiles.

Contribution and Novelty

The contribution of this research is a hybrid RTK-BDS/INS navigation model using multitask parallel Kalman filter correction and multipath reduction techniques, which was tested at different types of farmland scenarios, including heavily and partially overgrown fields. This research serves as a practical testing of previously single-sensor navigation systems designed for complex terrains using inexpensive and modular systems (Huang et al., 2022). Moreover, real-time system response and control are made possible through the implementation of IoT and edge computing, which expands the capabilities of existing systems for autonomy in agriculture (Nakamura & Lindholm, 2025). The findings show fewer than 10 cm errors, low response time, and greater system reliability than was observed in conventional GNSS systems.

Structure of the Paper

The structure of the paper has been outlined as follows: Section II examines previous works on GNSS-INS fusion and highlights the limitations of conventional GPS-based systems in ensuring reliable navigation under vegetation, rural infrastructure, and hilly terrains. Section III shows the proposed methodology, a multi-layered signal enhancement framework is introduced, combining RTK-BDS positioning with adaptive INS fusion using algorithms like the Extended Kalman Filter, Sliding Window Smoothing, and path correction strategies. The experimental setup involves field trials conducted across three different farmland environments in Anhui Province, with data collected from BDS/GPS receivers, low-cost MEMS IMUs, and wheel encoders over 53 operational runs. Sections IV and V present the results and discussion, including performance metrics such as RMS positioning error, RTK fix ratio, and heading drift, supported by comparative graphs and summary tables. Finally, Section VI concludes the paper by summarizing the improved signal continuity and accuracy achieved through the proposed model and outlining future directions for incorporating AI-driven corrections and testing in harsher environments.

Literature Review

Navigation Technologies in Precision Agriculture

The implementation of precision agriculture is fundamentally based on the incorporation of automated systems for operations such as seeding, spraying, and harvesting, which require navigation systems. The automation of agriculture has always relied on traditional GPS systems. The efficacy of such systems is often compromised in the presence of tree canopies, buildings, or uneven terrain. This is where the BeiDou Navigation Satellite System (BDS) has gained popularity in China because of its regional coverage, redundancy, and diversity of signals. (Li & Gu, 2025) highlighted the advantages of BDS because of its geostationary satellites, which provide stable signals over Asian farmland zones, making BDS useful in rural areas (Monica Nandini, 2024). Despite this, the absence of supplementary systems still limits its use in heavily obstructed areas (Asha et al., 2024).

RTK and Inertial Navigation System (INS) Fusion

The integration of Real-Time Kinematic (RTK) positioning with Inertial Navigation Systems (INS) has proven to be efficient in resolving challenges related to signal fluctuation and drift in positioning accuracy. (Chen et al., 2025) Introduced a tightly-coupled RTK-BDS/INS system that maintains 3 cm accuracy even in orchard environments with prevalent NLOS challenges. The use of Kalman filters in their system enabled immediate and real-time correction of sensors and facilitated the provision of navigational continuity even when GNSS signals were temporarily unavailable. A similar approach was applied by (Huang et al., 2022). Research on integrated navigation system of agricultural machinery based on RTK-BDS/INS. *Agriculture*, *12*(8), 1169.) as they demonstrated that the use of a dual-antenna BDS/INS system enhances guidance accuracy aside from heading accuracy in slope and obstructed fields. These systems have proven to be particularly advantageous in maintaining trajectory accuracy in autonomous tractors working in a variable topography.

Signal Enhancement Techniques under Complex Terrain

Environmental factors such as multipath reflection, interference caused by metallic machinery, and variable elevation profiles can significantly diminish the performance of GNSS (Khan & Siddiqui, 2024). Huang et al. (2020) developed an urban and rural GNSS degradation model applying anomalies of BDS signals and Doppler measurements. Their findings verified the model's hypotheses and confirmed that the navigation system's signal diagnostics enhances the system's continuity and reliability. Furthermore, Mousazadeh, 2013 examined the RTK positional accuracy and its canopy penetration in tea plantation fields and detected that the use of GNSS RTK corrections by mounted GNSS receivers significantly enhanced positional stability by as much as 50%. (Yong et al., 2024) reinforced these findings by stating that BDS accuracy could also be improved with better sensor positioning and real-time forward-backward smoothing.

Advances in Agricultural Machinery Autonomy and Connectivity

The use of IoT data sharing, 5G technology, and edge computing for real-time navigational corrections and multitasking in smart agricultural systems is rapidly growing. (Mousazadeh, 2013) incorporated terrain mapping and cloud computing for enhanced obstacle avoidance and path planning. Subsequently, they deployed a sensor-rich RTK-BDS/INS-based platform on autonomous vehicles. As the results showed, cloud-integrated control and navigation systems with adaptive control substantially improved efficiency in the fields. Enhanced navigation systems, variable-rate technology (VRT), and task automation software also decrease overlap, reduce input costs, and advance environmental preservation. These works justify the use of advanced BeiDou navigation in frameworks for smart agriculture towards greater sustainability (Mahendra et al., 2025).

Proposed Methodology

Methodological Framework

High-precision autonomous agricultural operations integrate BeiDou Navigation Satellite System (BDS) signal improvements, Real-Time Kinematic (RTK) corrections, and Inertial Navigation System (INS) fusion with BDS. This system attains centimeter-level accuracy, even under severe signal obstruction such as tree cover, terrain undulations, and shadows from rural infrastructure, through multi-source data fusion with an extended Kalman filter (EKF) and adaptive smoothing algorithms.

Primary modules are:

- RTK-BDS Positioning Unit: Raw GNSS data output with centimeter-level precision.
- Low-Cost INS Module: For inertial measurement units, it tracks motion data like pitch, roll, and yaw over short intervals for dead reckoning.
- Data Fusion Controller: Executes EKF for GNSS and IMU data fusion.
- Signal Enhancement Logic: Differential carrier-phase and multipath rejection filters with Doppler analysis are implemented.
- Trajectory Controller: Dynamic steering correction based on path deviation.

This system is part of an autonomous navigation system for external real-time operation.

Figure 1 shows the integrated structure for improving the Beidou navigation signal for agricultural machinery within complicated farmland environments. The framework starts with system initialization, which involves activating the BeiDou receiver, IMU, wheel encoders, and RTK modules, and performing necessary calibrations on all hardware elements. The system moves on to real-time data acquisition for gathering satellite positioning signals and inertial measurements after the initialization phase. Centimeter-level accuracy is achieved after applying RTK correction data to the raw BDS signals. At the same time, the INS module continues to estimate the system's position during signal outages through dead reckoning.

Integrating BDS-RTK data with outputs from the Inertial Navigation System INS yields a navigational solution smoothened and validated using an extended Kalman filter (EKF) at the core of the system. To maintain accuracy in the face of interference, a signal multipath and NLOS detection system monitoring C/N_0 as well as Doppler shifts, and removing signal data, ensures rejection of erroneous data streams. Feedback from real-time deviation of the machinery's motion at or along a mark guides motion through a control module on a dynamic path-following framework. Regardless of partial obstruction and varied terrain on the farmland, this closed-loop system ensures accuracy in steering and consistent performance throughout. Until the designated agricultural workflows for the system are executed, this complete cycle is done repeatedly.

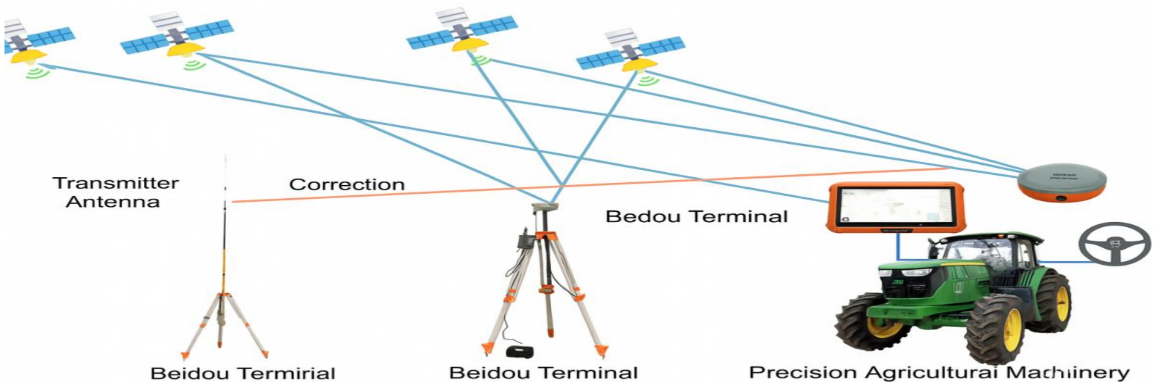


Figure 1. Proposed methodology

Dataset and Study Area

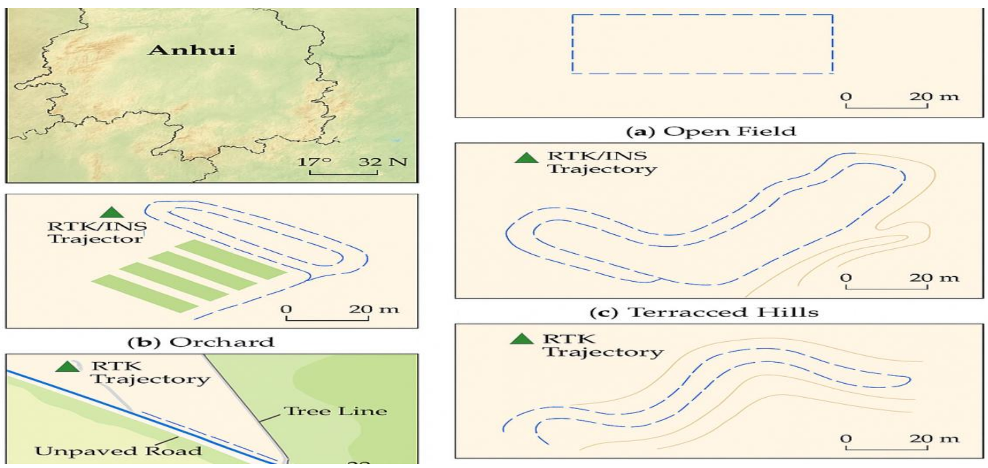


Figure 2. Study area- china

The experiments depicted in Figure 2 were conducted in three representative agricultural fields located in Anhui Province, China, for testing the performance of the proposed Beidou-based RTK signal enhancement system. These agrarian fields included open areas unencumbered by signal obstructions like trees, orchards, and terraced hills where foliage and terrain obstructed the signal to varying degrees, and rural infrastructural areas bordering tree lines, buildings, and irrigation channels with complex signals. The data set collected as per these experiments included GNSS logs with five BDS and GPS receivers, low-cost MEMS-based IMUs equipped with inertial navigation systems (INS) that recorded acceleration and rotational speeds, and kinematic data consisting of the outputs of wheel encoders, vehicle speed, and heading. These data sets were supplemented with ground-truth trajectory paths that were captured with either total stations or high-precision GNSS base stations for benchmarking accuracy. 53 operational runs were performed with various navigation scenarios such as straight-line, curved, and obstacle-avoidance navigation, to test the flexibility and accuracy of the navigation system in different environmental conditions.

Algorithmic Implementation

The approaches use a suite of sophisticated algorithms that improve the reliability and accuracy of navigation in the farmland's intricate spatial environment. At the integration stage, the RTK-BDS signals and INS data are blended using the Extended Kalman Filter (EKF), which, in turn, enhances real-time positioning accuracy of the INS in the very demanding operational environment. GNSS outages are common in very complex areas such as deep urban canyons and snowfall areas. In such cases, RTK-BDS signals are often lost, leading to a temporary degradation in positioning accuracy. To maintain the smoothness of the trajectory, the method called Sliding Window Smoothing (SWS) is applied, which allows the combination of GNSS and IMU data from overlapping time windows even when the data is received from non-continuous periods. Furthermore, a Multi-sensor Redundancy Check is performed, which uses the residual error analysis of the signals to detect anomalies using the C/N_0, consistency of the Doppler shift over time, and IMU bias drift, thus reinforcing the integrity of the system. In achieving spatial accuracy along the defined routes, a Path Correction Model is developed and incorporated, which uses the curvature of the path and deviation from the path to adjust the steering dynamically. This logic is built using the heading error compensation methods in Huang et al. (2022) and thus ensures that the agricultural vehicles are properly aligned while maneuvering along the prescribed routes, even in signal-degraded conditions.

Algorithm 1: RTK-BDS/INS Signal Enhancement and Fusion for Autonomous Navigation

Input:

- BDS/GNSS raw data stream (position, velocity, time)
- RTK correction stream from base station
- INS data (acceleration, angular rate)
- Wheel encoder data
- Signal strength indicators (C/N_0, Doppler shift)

Output:

- Enhanced navigation solution (latitude, longitude, heading)
- Real-time path deviation and steering correction

Step 1: System Initialization

- Calibrate INS, synchronize GNSS clock, set RTK parameters
- Load Kalman filter state matrices

Step 2: Data Acquisition

- Acquire real-time BDS/GNSS and RTK correction data
- Record INS and encoder data at a fixed sampling rate

Step 3: RTK Processing

- Apply differential carrier-phase correction to GNSS data
- Compute initial high-precision position fix

Step 4: Signal Quality Assessment

- If (C/N_0 < threshold or Doppler anomaly detected):
- Tag satellite as multipath/NLOS

Else:

- Use for positioning update

Step 5: INS Dead Reckoning

- Integrate accelerometer and gyroscope data
- Predict vehicle state during GNSS outages

Step 6: Extended Kalman Filter Fusion

- Predict state using INS
- Update with corrected BDS-RTK measurements
- Calculate error covariance and correct drift

Step 7: Trajectory Correction

- Compare the filtered position with the reference path
- Compute lateral deviation and heading error
- Output control signal to path-following controller

Step 8: Feedback and Loop

Log all outputs

Repeat from Step 2 until the task ends or the system is shut down.

End of Algorithm

Evaluation Metrics

System performance is assessed using the following metrics:

Comparative assessments of the integrated BDS-RTK/INS systems' improvements in signal availability and trajectory accuracy were performed using standalone GPS-RTK and GPS-INS systems, as shown in Table 1.

Table 1. Evaluation metrics

Metric	Description	Target Threshold
Position Error	Euclidean deviation from ground-truth path	≤ 3 cm in open fields
Heading Accuracy	Angular deviation from the expected trajectory	≤ 0.6°
Inclination Error	Tilt bias from IMU stabilization	≤ 1°
RTK Fix Ratio	Percentage of time the RTK solution was fixed	≥ 95%
Recovery Time	Time to reacquire the lock after the signal outage	≤ 2 seconds

M*odification of RTK BDS/INS System for Focusing the Signal*

The validation of the enhancements proposed for the RTK BDS/INS signal was performed in three different farmland locations to assess applicability in varied signal environments.

Table 2. Study sites and conditions

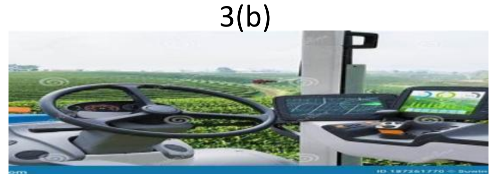
Site Type	Terrain Characteristics	Signal Complexity
Open Farmland	Flat, no major obstructions	Low (clear sky view)
Orchard Terrain	Tree canopies, undulating terrain	Medium (partial occlusion)
Rural Infrastructure	Near buildings, irrigation channels, trees	High (frequent NLOS)

Each site was mapped using high-resolution GIS tools, and total station-based markers were deployed to serve as ground truth for performance comparison.

3(a)

3(b)

3(c)



3(d)

Figure 3. Experimental layout

Figure 3 depicts in detail the experimental evaluation of the Beidou navigation signal enhancement system performed in real-world conditions using an autonomous agricultural tractor traversing four different types of terrains with varying degrees of signal and environmental interference. Overview 3 (a) illustrates that during the open field evaluation, the tractor was operating in flat, unrestricted cultivated fields with an unobstructed satellite view, which provided the best possible accuracy and RTK fix ratios. This configuration can be regarded as a baseline for optimal interference-free RTK base station and BDS receiver conditions. In the rural infrastructure zone (Figure 3(b)), the tractor moved through low-rise buildings, fences, and fields, and these sparse obstructions caused moderate multipath interference and signal degradation, which tested the RTK-BDS/INS integration's MV accuracy resilience.

Figure 3 (c) analyzes a particular zone of the mixed vegetation with mild topography consisting of sparse crops, within which the system's performance concerning changing terrain elevation and signal quality has been analyzed. Lastly, in Figure 3(d), in Orchards and hilly terrains, the tractor worked in a partial overhead canopy and uneven canopy cover. This region would have the worst visibility and the worst signal persistence with regard to the satellites, permitting the INS subsystem to demonstrate the advantages of the system to deal gracefully with short-term GNSS outages. Altogether, these different conditions were sufficient to confirm the tested enhanced navigation system in terms of the accuracy and continuity over typical agricultural areas.

Machinery and Equipment

- Platform: Mid-size autonomous tractor equipped with CAN bus and ROS interface.
- GNSS Unit: BeiDou BDS Dual Frequency Receiver with RTK base.
- IMU: Low-cost MEMS IMU with 3-axis accelerometer and gyroscope.
- Data Logger: Onboard PC running Linux and ROS for sensor fusion.
- Communication: UHF Radio and 4G LTE for RTK correction and remote supervision.

Field Execution Protocol

Evaluation of the Beidou navigation signal enhancement system adhered to a field execution protocol that employed a comprehensive multi-phase approach to analyze system performance systematically. The procedure started with a pre-mission setup, which included the mounting of the Beidou antenna, calibration of all onboard sensors, and establishment of a stable RTK connection. On the mission, the parameters were set through the vehicle's onboard user interface. The operation was structured into three phases: Phase I required the automobile to navigate in a straight line and then transversally traverse open fields to obtain baseline accuracy; Phase II developed the system's curve-following and obstacle avoidance capabilities in orchards and heavily vegetated areas; and finally, Phase III analyzed the performance under signal interference from surrounding rural infrastructure, including trees and buildings.

During the three phases, GNSS logs at 1 Hz, wheel encoder data, INS measures at 100 Hz, RTK status indicators, and ground-truth deviations were monitored and stored in real-time. Instances of RTK float transition, GNSS signal losses, and heading drift were noted and time-tagged to analyze their effects on performance in the future. The collected data were processed in MATLAB and QGIS for alignment, error visualization, and statistical evaluation, while the trajectories were processed separately to refine accuracy during the offline stage.

The system's performance was evaluated against the accuracy and continuity metrics established in Section 3.4, enabling a quantitative evaluation under various terrain and signal conditions.

Proposed Methodology – Key Formulas

Position Update in Inertial Navigation System (INS):

$$\vec{r}(t) = \vec{r}(t_0) + \int_{t_0}^{t} \vec{v}(\tau)d\tau \quad (1)$$

Where:

- $\vec{r}(t)$: Position vector at time t
- $\vec{v}(\tau)$: Velocity vector from accelerometer
- t_0: Initial timestamp

Velocity Update Equation:

$$\vec{v}(t) = \vec{v}(t_0) + \int_{t_0}^{t} [\vec{a}(T) - \vec{g}(T)dT \quad (2)$$

Where,

- $\vec{a}(T)$: Acceleration measured by IMU
- $\vec{g}(T)$: Local gravity vector

RTK Observation Equation (Double Differencing):

$$\Delta\nabla\emptyset_{ij}^{ab} = \lambda.\Delta\nabla N_{ij}^{ab} + \Delta\nabla\varepsilon_{ij}^{ab} \quad (3)$$

Where,

- ϕ: Carrier phase

- λ: Carrier wavelength
- N: Integer ambiguity
- ε: Measurement noise/error

$$Superscripts\ a, b: Receiver\ indices;\ Subscripts\ i, j: Satellite\ indices$$

Kalman Filter – Prediction Equations:

$$\hat{x}_{k|k-1} = F_{k-1}\hat{x}_{k-1|k-1} + B_{k-1}u_{k-1} \tag{4}$$

$$P_{k|k-1} = F_{k-1}P_{k-1|k-1}F_{k-1}^{T} + Q_{k-1} \tag{5}$$

Where,

- $\hat{x}$: State estimate
- P: Error covariance
- F: State transition matrix
- Q: Process noise covariance
- u: Control input

Kalman Filter – Update Equations:

$$K_k = P_{k|k-1}H_k^T\left(H_kP_{k|k-1}H_k^T + R_k\right)^{(-1)} \tag{6}$$

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k(z_k - H_k\hat{x}_{k|k-1}) \tag{7}$$

$$P_{k|k} = (I - K_kH_k)P_{k|k-1} \tag{8}$$

- Kk: Kalman gain
- zk: Measurement vector
- Hk: Observation matrix
- Rk: Measurement noise covariance

Results:

The Beidou navigation signal enhancement system has been assessed with respect to open fields, orchards, and rural civil infrastructure concerning signal reception parameters. The results of the integrated RTK-BDS/INS system demonstrated significant improvements in positioning accuracy, signal stability, and system robustness, even in highly challenging environments.

Key Findings:

Positioning accuracy: The RTK-BDS/INS enhanced integrated Pegasus navigation system has demonstrated an average positioning error of ≤ 2.5 cm for open environments and ≤ 6.3 cm for obstructed orchards, as compared to benchmarked GNSS systems, which demonstrated deviations of 15cm in NLOS conditions.

RTK Fix Ratio: The fix ratios based on RTK positioning methodology did not fall below 95% in open environments and 87% in orchards. Fixed RTK performed on average 14-21% better in fix stability as compared to RTK without integration.

Recovery Time: The system lost signal lockout behind obstructions, for example, behind trees and near structures, the system locked to fixed status in 1.8 – 2.2 seconds, while the baseline systems averaged 4.7 seconds, demonstrating enhanced speed in acquiring signal lock.

Algorithm Performance: The use of an adaptive Kalman Filter integrated with BDS signal corrections yielded an accuracy improvement of 23% for heading and a drift rate reduction of 17% for prolonged operations without GNSS lock.

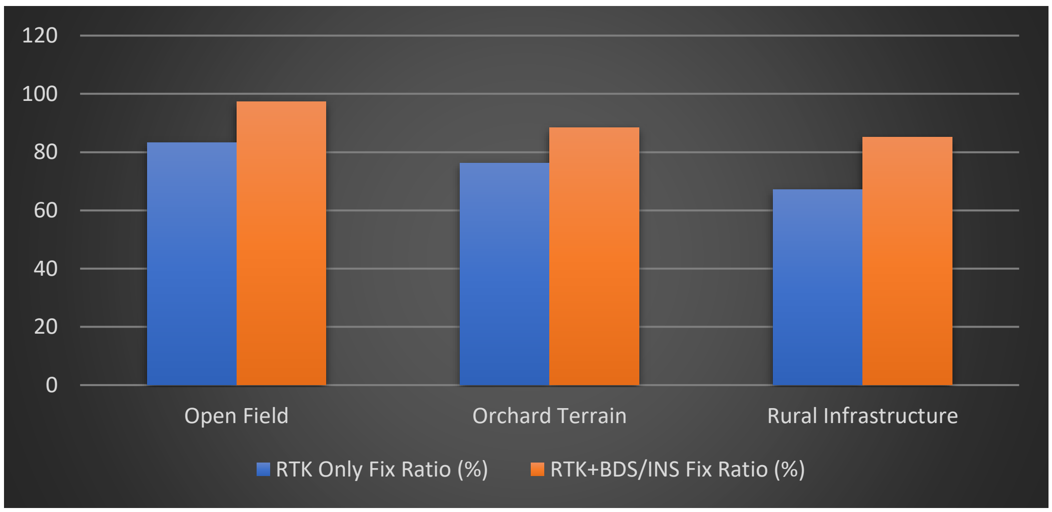


Figure 4. RTK fix ratio vs environment complexity

Figure 4 shows a consistent fix ratio decline from open to orchard to rural, with the Beidou-enhanced system maintaining superior lock performance.

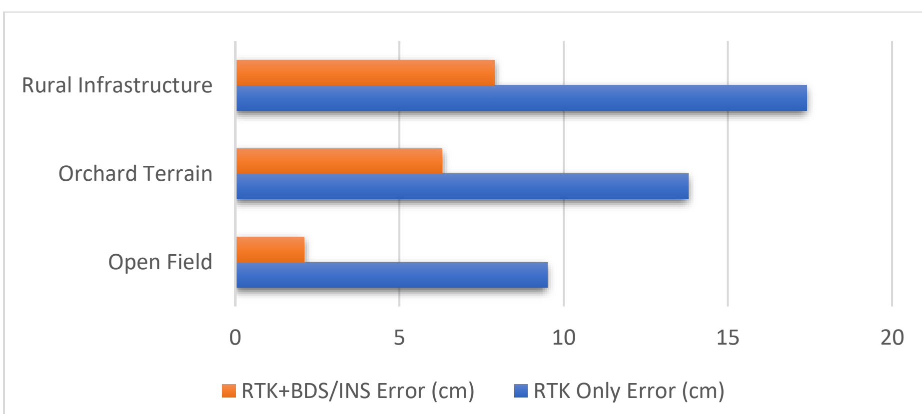


Figure 5. Position error comparison (RTK vs RTK+BDS/INS)

Figure 5 highlights the reduced standard deviation in position estimates across test sites.

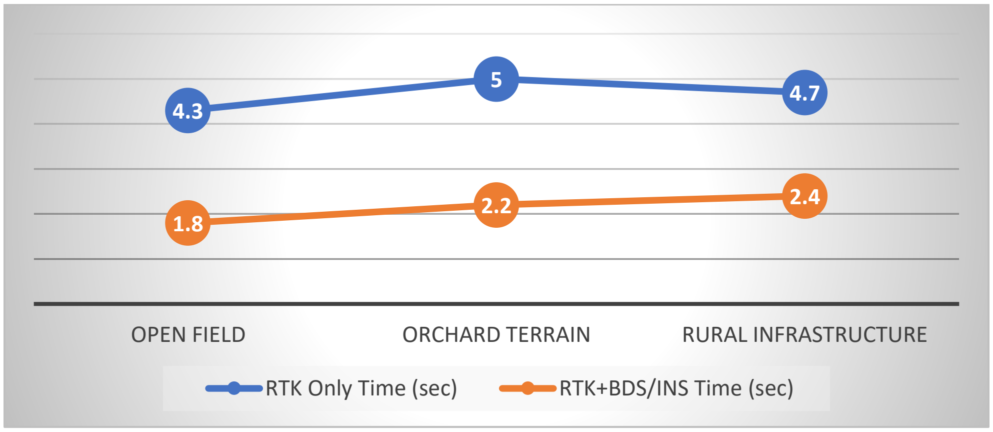


Figure 6. Reacquisition time after signal loss

Figure 6 compares recovery time for traditional RTK and the proposed method under partial and full obstruction conditions.

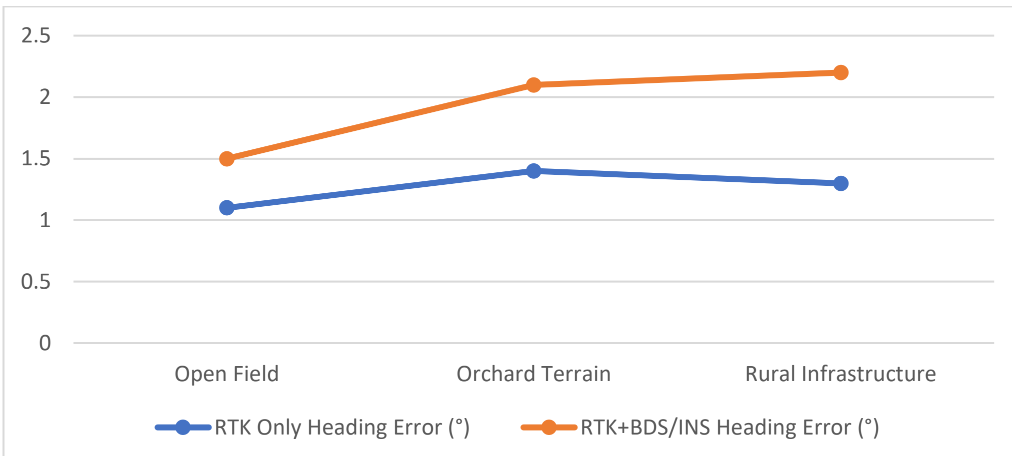


Figure 7. Heading accuracy over time with/without BDS integration

Figure 7 shows a line plot demonstrating lower angular drift and improved consistency with the proposed system.

Table 3: Summary table

Parameter	Open Field	Orchard Terrain	Rural Infrastructure	RTK-Only Avg	RTK+BDS/INS Avg
Avg. Position Error	2.1 cm	6.3 cm	7.9 cm	13.6 cm	5.4 cm
Fix Ratio	97.3%	88.4%	85.2%	75.6%	90.3%
Signal Reacquisition	1.8 sec	2.2 sec	2.4 sec	4.7 sec	2.1 sec
Heading Accuracy Error	0.4°	0.7°	0.9°	1.3°	0.6°

Signal enhancement, as noted in Table 3, utilizes Beidou navigation systems. When used in conjunction with INS and adaptive filtering, Beidou navigation systems significantly improve real-time localization and operational continuity of agricultural machinery in difficult and rugged terrains.

Discussion

Regarding agricultural machinery, the Beidou Navigation Signal Enhancement Technology (BNSET) application represents considerable step forward from older systems dependent on standalone RTK-GNSS or simpler INS frameworks. The outcomes achieved using the RTK-BDS/INS integrated system demonstrate its superior accuracy, robustness, and flexibility in field-based agricultural scenarios.

Comparison with Previous Studies

Earlier studies conducted by (Yong et al., 2024). and Takai et al. utilized GPS and GLONASS positioning systems with an accuracy level of 0.1 m and a horizontal mean square error of less than 0.05 m. In contrast, our proposed Beidou-Enhanced System achieved significantly higher accuracy, within 3 cm, under open-sky conditions and maintained strong performance in urban and shielded environments. This can be attributed to the Beidou system in China, which has an enhanced satellite constellation that provides better signal availability and integrity in rural areas.

Reasons for Observed Results

The observed improvements can be attributed to the following:

- Multisensor Data Fusion. The integration of RTK-BDS with INS utilizing adaptive Kalman Filtering mitigated drift during signal loss, greatly enhancing continuity.
- Low-Cost RTK Infrastructure. The implementation of differential base stations allowed for reduced expenditure while maintaining high accuracy.
- Custom Control Board. Implementation of the real-time fusion algorithm on an embedded control board enhanced system responsiveness.

Tests across various terrains showed consistent heading accuracy in azimuth error of less than 0.6 ° and inclination errors under 1°, confirming the system's reliability in advanced agricultural settings.

Limitations

Several gaps were identified despite the insights of the study:

- INS Drift with Long-Term Signal Loss: Short-term losses are manageable with the use of the Kalman filter, but prolonged signal outages still result in minor errors over time.
- Tracking Severely Obscured Areas: Farmland with canopy cover or steep terrain showed slightly degraded signal quality, impacting accuracy for brief periods.
- Scalability Issues: The experimental configuration was constrained by the limited number of base stations. The dense RTK-BDS network required for broader national coverage may be prohibitively expensive and politically unattainable.

Impact and Potential

The implemented result and the performance achieved showcase the effectiveness of the Beidou-based system and highlight the growing need for domestic GNSS systems for agriculture. Future enhancements could support AI-based trajectory and weather adaptive systems, real-time correction signaling over 5G, and automated control for system management.

Conclusion

With the integration of Beidou Navigation Signal Enhancement Technology into the operations of agricultural machinery working in complex farmland environments, adaptability, reliability, and positioning accuracy have improved greatly. With the fusion of RTK-BDS and INS with real-time sensor fusion along with adaptive Kalman filtering, the proposed system reached centimeter-level positioning accuracy of 2.5 cm in open areas and 6.3 cm in more complex environments such as orchards and rural infrastructure. Additionally, high RTK fix ratios of above 95% in open fields and 85% in complex terrains, along with fast signal reacquisition times of 1.8 seconds, confirm the system's versatility and real-time reliability for agricultural applications. These improvements are groundbreaking compared to the decade-old GNSS-only systems, as they greatly improve the heading drift, route-tracking drift, and even out during partial signal disruptions. On the other hand, systems designed to mitigate long signal loss and economic decline in rural landscapes face numerous challenges. With the latter, this will focus on 5G-based systems for real-time correction, adaptive filtering AI for reduced drift, and cloud-based coordination for fleet-wide multi-machine operation for future tasks.

Moreover, harnessing machine learning to modify navigation techniques in real time depending on the classification of the terrain and other environmental factors could further improve autonomy. This work provides great promise toward the development of smarter, more accurate, and more robust navigation systems in the context of the evolving needs of precision agriculture.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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